Perspectives on heavy-quarkonium production at the LHC

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Abstract.
We summarise the perspectives on heavy-quarkonium production at the LHC, both for
proton-proton and heavy-ion runs, as emanating from the round table held at the HLPW
2008 Conference. The main topics are: present experimental and theoretical knowledge,
experimental capabilities, open questions, recent theoretical advances and potentialities
linked to some new observables.

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1. INTRODUCTION

With the start-up of the LHC approaching, it is certainly expedient to make an overview on what we currently know on quarkonium production, both in proton-proton and heavy-ion collisions and on what we can expect from analyses to be carried at the LHC. Heavy-quarkonium production mechanism has always been – and still is – a subject of debate (for reviews see [1, 2, 3, 4, 5]). Heavy quarkonia have been often suggested as ideal probes in studies and analyses of complex phenomena. However, reality was later found to be much less simple than initially thought. A well known example is the suggestion to measure the suppression of J/ψ production in heavy-ion collision as a smoking-gun signature of the creation of the quark gluon plasma (QGP) [6]. However, cold nuclear matter effects, such as shadowing, energy loss, absorption, etc. , were shown to play an important role and had to be considered in the interpretation of the experimental measurements. Furthermore, effects of the successive dissociations of higher-excited states which can decay into J/ψ (ψ', χ_c) had to be taken into account, as well as more specific issues related to the description of the plasma itself.

In fact, even in a much "cleaner" environment, such as in *pp* collisions, understanding quarkonium production has been a challenge since the first measurements by the CDF Collaboration of the *direct* production of J/ψ and ψ' at $\sqrt{s} = 1.8$ TeV [7, 8]. It is fair to say that, at present, a consistent theoretical picture that predicts both cross sections and the polarisation measurements for charmonium at

the Tevatron [9], along with the cross section from PHENIX at RHIC [10] is not available. For instance, the long-standing prediction of Non Relativistic QCD [11] (NRQCD) on the transverse polarisation of ψ's at high transverse momentum is not supported by the data. The most natural interpretation of such flagrant failure of NRQCD is that the charmonium system is too light for relativistic effects to be neglected.

Indications that this might be indeed the case come from the agreement between theory and the available experimental data for Υ production in pp (and inclusive decays). In this case, relativistic corrections are expected to be less important and the leading state in the Fock expansion, i.e. the heavy-quark pair in a colour singlet $^3S_1$ to be dominant. The latest NLO predictions [12] which include some of the important NNLO α_S^5 corrections, show a satisfactory agreement with the data coming from the Tevatron [13, 14]. Once again, much is expected from polarisation measurements at the Tevatron and the LHC to confirm that at least bottomonium predictions are well under control.

In pA collisions, LHC measurements will certainly be of greatest importance to pinpoint the size of shadowing effects in the small x region which can also be studied via electromagnetic (aka. "ultraperipheral") AA collisions. Furthermore, data will allow to understand the absorption mechanisms at high-energy and subsequently to gain insights of the different formation time of the various heavy quarkonia.

Finally, nucleus-nucleus collisions at the LHC will be the long-awaited ideal laboratory for the study of the QGP. Unprecedented temperatures will be reached; in conjunction with the high-luminosity beams, bottomonia will be at last promoted as a practical probe for the QGP formation. With the good news from higher-order QCD-correction studies centered on Υ, we are certainly at the beginning of very exciting discovery years.

2. EXPERIMENTAL CAPABILITIES

2.1. ALICE (by Andry M. Rakotozafindrabe)

ALICE is the LHC dedicated heavy-ion experiment. Its main physics goal is to study the properties of the hot and dense deconfined hadronic matter which is expected to be created during the relativistic heavy ion collisions. ALICE's primary interest into the production rate of the heavy-quarkonium states lies into the fact that it can be used as a sensitive probe to the formation of the quark-gluon plasma. At temperatures above the quarkonium binding energy, the latter is foreseen to melt through colour screening, inducing a suppression of the production rates. The dissociation temperature T_d pattern would be:

$$T_d[\psi'] \approx T_d[\chi_c] < T_d[\Upsilon(3S)] < T_d[J/\psi] \approx T_d[\Upsilon(2S)] < T_d[\Upsilon(1S))] \tag{1}$$

which shows how quarkonium suppression can be used to estimate the temperature of the created QGP. Lower energy accelerators/colliders (SPS and RHIC) have indeed observed J/ψ suppression. For the Υ family, this will be only feasible at the LHC where the $b\bar{b}$ production cross-section is quite sizeable, and where

$T_d[\Upsilon(1S)]$ can be reached. Moreover, at nominal luminosity, central *PbPb* collisions at the LHC ($\sqrt{s_{NN}} = 5.5$ TeV) are expected to produce about a hundred of $c\bar{c}$ pairs, which substantially increases the regeneration probability of secondary J/ψ's. This emphasises the interest in measuring the $\Upsilon(2S)$ production rate, since it is expected to benefit from a small regeneration probability (about only five $b\bar{b}$ pairs are expected in central *PbPb* collisions). An important remark is that in-medium effects on charmonia can be studied once the feed-down from B decays is properly subtracted ($B \to J/\psi + X$, expected to account for about 20% of the total J/ψ yield if no cold nuclear matter effect is considered). Obviously, results obtained in AA collisions must be benchmarked against the ones from pp collisions, but also pA collisions in order to get the baseline for the cold nuclear effects.

The LHC program plans pp running at $\sqrt{s} = 14$ TeV for 8 months per year (10^7 s effective time) followed by ion running for one month per year (10^6 s). ALICE can participate to pp running, but at a maximum allowed luminosity of $5\,10^{30}$ cm^{-2} s^{-1}. The first heavy-ion run will be *PbPb* collisions at $\sqrt{s_{NN}} = 5.5$ TeV at a luminosity of $5\,10^{25}$ cm^{-2} s^{-1}, corresponding to $1/20^{\text{th}}$ of the design luminosity. One or two years of light-ion collisions ($ArAr$, with a luminosity up to 10^{30} cm^{-2} s^{-1}), and one year of pPb collisions at $\sqrt{s_{NN}} = 8.8$ TeV are also planned.

ALICE [15, 16] can detect quarkonia in the dielectron channel at central rapidity ($|\eta| < 0.9$), and in the dimuon channel at forward rapidity ($-4 < \eta < -2.5$). In these rapidity ranges, the corresponding probed Bjorken-x approximately goes from 10^{-2} to values as low as 10^{-5}, providing additional insight into the PDFs and their modification in the nuclear environment. The central barrel and the muon arm are equipped with dedicated triggers on the individual electron and muon transverse momentum. In order to select a lepton pair from quarkonium decays, a low-P_T trigger cut is applied on individual leptons to remove most background sources: $P_T > 3$ GeV/c for single electrons and $P_T > 1\,(2)$ GeV/c for single muons from charmonia (bottomonia). As a consequence, it prevents the detection of charmonia with $P_T < 5$ GeV/c in the dielectron channel, whereas the charmonia can be detected down to very low P_T (about a hundred of MeV/c) in the dimuon channel. The high P_T reach is expected to be $10\,(20)$ GeV/c for the J/ψ into dielectrons (dimuons) for a *PbPb* run of one month at nominal luminosity. In both channels, the expected mass resolution of about 90 MeV/c^2 will be sufficient to resolve all the Υ states. The expected mass resolution for the J/ψ is about $30\,(70)$ MeV/c^2 in the dielectron (dimuon) channel. The central barrel has excellent secondary vertexing capabilities, combined with particle identification. Therefore, prompt and secondary J/ψ, from B decays, can be distinguished at central rapidities via a displaced vertex measurement. At forward rapidity, this technique is not usable: the prompt J/ψ yield has to be determined indirectly, by subtracting from the measured yield the one expected from B decay. The latter is inferred from the single-muon P_T-spectra measurement with the cut $P_T^\mu \gtrsim 1.5$ GeV/c applied to all reconstructed muons to maximise the beauty-signal significance. A fit technique is then applied to extract the P_T distribution of the muons from B decays [16]. Last, but not least, ALICE will be able to measure the J/ψ polarisation, both in pp and

PbPb collisions.

2.2. ATLAS and CMS (by Aafke C. Kraan and David d'Enterria)

The ATLAS [17] and CMS [18] experiments at the LHC are general purpose detectors designed to explore the physics at the TeV energy scale. The primary goals of the experiments are to reveal the electroweak symmetry breaking mechanism and provide evidence of physics beyond the Standard Model (SM) in proton-proton collisions at $\sqrt{s}$ = 14 TeV. The two experiments are obviously extremely well suited to carry out Quantum-Chromodynamics studies in both *pp* and *PbPb* collisions.

The total cross section for J/ψ and Υ production at *pp* collisions at 14 TeV are expected to be around 0.4 mb and 7 μb, respectively, and for the higher mass states an order of magnitude lower. The J/ψ and Υ measurements in ATLAS and CMS focuse normally in the dimuon decay channel $(J/\psi, \Upsilon \to \mu^+\mu^-)$ with branching ratios of $J/\psi \to \mu^+\mu^-$ and $\Upsilon \to \mu^+\mu^-$ are 5.98% and 2.48% respectively. On the one hand, the high centre-of-mass energies (up to 14 TeV) and luminosities (up to 10^{34} cm^{-2}s^{-1}) as well as the large-acceptance muon spectrometers ($|\eta|$ <2.5, full azimuth) available in the ATLAS and CMS experiments will allow, unlike the ALICE and LHCb cases, for quarkonium measurements at the LHC up to very large transverse momenta. On the other hand, the strong magnetic field and/or the large material budget results in lower reconstruction efficiencies for small transverse momentum muons (usually below $P_T \approx$ 3 GeV/c). Thus, the sensitivity for quarkonium measurements at low momentum is inferior than that of the Tevatron or ALICE and LHCb experiments. Only startup conditions, when the luminosities and muon trigger thresholds will be low, will allow for some lower transverse momentum measurements.

Besides physics measurements, during detector commissioning and startup, dimuon invariant masses of quarkonium states will provide extremely useful candles for detector calibration and alignment. Several physics analyses are planned at both ATLAS and CMS including:

- Differential inclusive cross section for J/ψ, Υ, $\psi(2S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, as well as the χ_c^0, χ_c^1, χ_c^2 states in *pp*, *pA* and *AA* collisions.
- Polarisation measurements of these states.
- More exclusive measurements aimed at understanding the underlying $Q\overline{Q}$ production mechanisms by looking, e.g., at the associated hadronic activity.

In Table 1 some relevant parameters for J/ψ's and Υ's are given for the ATLAS and CMS experiments [17, 18, 19, 20]. For the heavy-ion running, the performances of ATLAS [21] and CMS [22] are very similar to the proton-proton ones.

TABLE 1. Basic J/ψ and Υ reconstruction performances for ATLAS and CMS in pp collisions at 14 TeV.

	ATLAS	CMS
$Q\overline{Q}$ trigger threshold	$P_T^{\mu_1} > 6$ GeV/c, $P_T^{\mu_2} > 4$ GeV/c,	$P_T^{\mu_1} > 3$ GeV/c, $P_T^{\mu_2} > 3$ GeV/c
J/ψ mass resolution	~ 50 MeV/c^2	~ 30 MeV/c^2
$N_{\text{events}}^{\text{reco}}$ in 10 pb^{-1}	2×10^5	3×10^5
Υ mass resolution	~ 170 MeV/c^2	~ 95 MeV/c^2
$N_{\text{events}}^{\text{reco}}$ in 10 pb^{-1}	5×10^4	1×10^5

2.3. LHCb (by David d'Enterria)

The LHCb experiment [23] at the LHC is mainly focused on the search of possible signals of new physics in CP-violation and rare decays processes in the heavy-quark sector of the Standard Model (SM). For this purpose, the experiment has been equipped with arguably the best capabilities for the detection of b and c quarks produced at *forward rapidities* in proton-proton collisions at the LHC. Indeed, the LHCb detector – with a single-arm configuration – has excellent and varied particle detection and identification capabilities in the forward hemisphere. In particular, muons and electrons can be well measured in the pseudo-rapidity range $1.8 < \eta < 4.9$. For comparison, in the same η range ATLAS and CMS can only reconstruct electrons (in a reduced $2 \lesssim \eta \lesssim 3$ range), whereas ALICE can only measure muons (in a slightly more reduced acceptance: $2.5 < \eta < 4$, and only for proton-proton luminosities, 10^{30} cm^{-2}s^{-1}, 100 times lower than those available for LHCb). Those characteristics make of LHCb an excellent apparatus to measure forward quarkonium production cross-sections and polarisation via $J/\psi, \Upsilon \rightarrow e^+e^-, \mu^+\mu^-$, including the excited states ($\psi(2S)$, $\Upsilon(2S)$, $\Upsilon(3S)$).

3. OPEN ISSUES

3.1. pp collisions (by Andry M. Rakotozafindrabe and J.P. Lansberg)

The underlying theory for *direct* and *prompt* ψ is still under intense debate [1, 2]. Via the colour octet (CO) mechanism, NRQCD factorisation [11] has been successful to explain some features of the charmonium hadroproduction. As illustrated by the comparisons to CDF measurements in $p\bar{p}$ [7, 8] or to PHENIX old measurements in pp [24, 25]), for $P_T \gtrsim 5$ GeV/c, it provides a good description of the P_T-differential cross-section for the direct J/ψ and ψ', the cross-section being dominated by the gluon fragmentation into a colour-octet $^3S_1$ state. The latter mechanism leads to transversally polarised J/ψ and ψ'.

However, this is not seen by the CDF experiment [9] which measured a slight longitudinal polarisation for both the prompt J/ψ and direct ψ' yield. It is worth noting here that the feed-down from χ_c can influence significantly the polarisation of the prompt J/ψ yield – this was taken into account in the NRQCD-based predictions [26]. Moreover, the recent preliminary result from PHENIX [27] indicates a

polarisation compatible with zero for the total J/ψ production at forward rapidity $(1.2 < |y| < 2.2)$, but with large uncertainties.

It is therefore not surprising to observe a renewed interest in improving the present predictions for the colour singlet (CS) contribution, by computing the higher-order QCD (see section 4.1) corrections in α_S, or by "softening" some of the basic assumptions of the common approaches, as done in [28] via the consideration of the s-channel cut contribution. On the one hand, NLO [29, 30] and part of NNLO corrections [12] significantly enhance the quarkonium yields[1]. In the $\Upsilon(1S)$ and $\Upsilon(3S)$ cases, the dominant NNLO corrections to the colour singlet [12] suffice to successfully describe the measured P_T-differential cross-section of the direct yield [13, 14]. The polarisation predictions for the latter cases seem quite encouraging considering CDF [13] and $D\emptyset$ [32] measurements. Those corrections could be though still unable to bring agreement with the measured P_T-differential cross-section of the direct J/ψ, but dedicated further studies are needed.

On the other hand, by including s-channel cut contributions [28] to the usual production CS production mechanism one can reproduce the P_T-spectra up to intermediate values of the J/ψ's P_T, both at the Tevatron and at RHIC, and provide mostly longitudinally polarised J/ψ at the Tevatron. However, as expected [28], this approach underestimates the cross-section at large values of P_T.

In summary, the theoretical status sounds clearer for the bottomonia than for the charmonium production processes. Additional tests are undoubtedly needed beyond the *mere* measurements of inclusive cross section and polarisation at the LHC. For instance, the hadroproduction of J/ψ or Υ with a heavy-quark pair [30, 33] appears to be a new valuable tool to separately probe the CS contribution, at least dominant at low-P_T (below 15 GeV/c), as well as the study of the hadronic activity around the quarkonium (see section 5).

3.2. pA collisions (by Andry M. Rakotozafindrabe)

The interest of pA collisions is based on the possibility they open up to evaluate both the initial and final-state effects on heavy-quarkonium production in cold nuclear matter (CNM). Such baseline is mandatory to be able to draw conclusions about any further effects due to QGP formation in AA collisions. In the following, we will address a non-exhaustive list[2] of these CNM effects.

Initial-state effects. Heavy-quarkonium production mainly proceeds through gluon fusion at relativistic ion colliders. Therefore, the nuclear shadowing of initial

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[1] This sounds like a confirmation of the study [31] which dealt in a simplified way with NNLO corrections assimilable to LO BFKL contributions. However, this study could not provide a prediction for the P_T dependence: it only predicted an enhancement of some NNLO corrections for large s.

[2] For instance, let us mention a potential further significant effect due to charm-quark shadowing as computed in [34] in a light-cone Green function formalism.

gluons has been extensively investigated (see [35] for a recent review), together with its consequences on the charmonium production.

On the experimental side, the gluon nPDF[3] is loosely constrained at small values of Bjorken-x:

- On the one hand, the processes used – Deep-Inelastic scattering (DIS) and Drell-Yan – are mostly sensitive to the quark and antiquark densities. Therefore, the gluon density is indirectly constrained, either via the nucleon-structure-function deviations from the Bjorken scaling, caused by gluon radiation, or via sum-rules (conservation of the nucleon momentum distributed among all partons).

- On the other hand, there is no nuclear DIS data below $x \lesssim 5\,10^{-3}$ at perturbative values of the momentum transfer $Q^2 \gtrsim \Lambda^2_{\rm QCD}$, required for the validity of the DGLAP equations used to predict the evolution of nPDF with Q^2.

As a result, the extracted parametrisations of the ratios nPDF/PDF have large uncertainties at low-x: typically, for the gluon shadowing in Pb, the LO parametrisations EKS98 [36] and EPS08 [37] give values of nPDF/PDF that differ by about a factor of ten at $x = 10^{-4}$ and $Q^2 = 1.69$ GeV^2. EPS08 notably includes additional constraints from high-P_T ($P_T \geq 2$ GeV/c) hadron production measured by the BRAHMS experiment [38] at forward rapidities in dAu collisions at RHIC top energy. These data mainly probe gluons with $x \gtrsim 5\,10^{-4}$ in the gold nucleus and suggest a much stronger shadowing. The discrepancy is even larger when these LO parametrisations are compared to the NLO ones, either nDSG [39] or HKN07 [40]. All these uncertainties preclude yet reliable predictions of heavy-quarkonium production at the LHC, dominated by low-x gluons (see Section 2.1).

A workaround to the use of these parametrisations can be found in approaches that try to describe the shadowing in a formal way:

- The underlying physical mechanism is thought to be multiple-scattering (or multi-pomeron exchanges) with initial interactions between the pomerons, and the calculations are made in the Glauber-Gribov framework [41]. However, these models usually have a narrower validity range (limited to the low-x region [42]) since they were designed to describe the coherence effects that lead to the depletion of the nuclear structure function. Indeed, at intermediate values of x, the amount of anti-shadowing appears to be smaller in these approaches than in the aforementioned parametrisations (for instance, see the comparisons reported in [43] for the J/ψ shadowing in dAu at RHIC).

- The Colour Glass Condensate (CGC) is an effective theory which describes the behaviour of the small-x components of the hadronic wavefunction in QCD (see [44] for a recent review). Hence, it can be used to study the high energy scattering in QCD, namely the initial stages of heavy-ion collisions. The theory is characterised by a saturation scale Q_s^2: at any Q^2 below this scale, the rapid rise of the gluon density at small-x slows down to a logarithmic rate, due to

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[3] nPDF stands for the parton density within a bound nucleon.

a growing number of gluon-gluon fusions. It is of no doubt that pA collisions at the LHC will provide crucial tests of the CGC framework, since they will allow to deeply probe the saturation region. At RHIC, the understanding of the initial effects on charmonium production in the CGC framework is still a work in progress. A first step was the calculation [45] of the open charm production, which is found suppressed at forward rapidity at RHIC. Predictions for the J/ψ are under way: for rapidities $y \geq 0$, a rather qualitative agreement with PHENIX dAu data is obtained in [46] [4] for the y-dependence and for the centrality dependence [5].

To summarise, the amount of shadowing crucially depends on x. By taking the J/ψ transverse momentum P_T into account when evaluating x_1, x_2 (and Q^2), the influence of P_T on the shadowing is investigated in [43, 51] at RHIC. There is an on-going debate on the way the J/ψ acquires its P_T: either *(i)* the initial gluons carry an intrinsic transverse momentum and the latter is subsequently transferred to the J/ψ ($2 \to 1$ process), or *(ii)* the P_T comes from the emission of a recoiling outgoing gluon ($2 \to 2$ process). For the latter process, the authors consider the partonic cross-section given in [28] which satisfactorily describes the J/ψ P_T-spectrum down to $P_T \sim 0$ at RHIC. On the average, initial gluons involved in these processes originate from different x-regions, hence resulting in quite different shadowing effects [51]. The present uncertainties on PHENIX dAu data [49] do not allow to discriminate these scenarios, but forthcoming improvements will be obtained from the recent data taking (with at least a factor of 30 in statistics).

Additional initial-state effects are the initial-partonic multiple scattering and the related parton energy loss. It is believed that the observed broadening of $\langle P_T^2 \rangle$ – the mean value of the J/ψ's transverse momentum squared – from pp collisions to pA collisions (with increasing A) is due to such multiple-scattering (the so-called "Cronin effect"). This effect is usually described as a random walk of the initial-projectile parton within the target nucleus (see e.g. [52, 53]): the resulting $\langle P_T^2 \rangle$ proportionally increases with the amount of scattering centers, characterised by the length L of nuclear matter traversed. Simple linear fits to $\langle P_T^2 \rangle$ vs L can indeed account for the pA measurements done at SPS. All pA and AA results at SPS, but the preliminary result reported by NA60 in pA at 158 AGeV, exhibit the same slope [54]. At RHIC, the $\langle P_T^2 \rangle$ measured in dAu [49] suffers from large uncertainties, but is compatible with a moderate broadening. A linear fit done to all data points available at RHIC (pp, dAu, $CuCu$ and $AuAu$) is reported in [55]: the slope is compatible with zero at mid rapidity and with some broadening at forward rapidity. Interestingly, within the large uncertainties, the slope seen at forward rapidity at RHIC is compatible with the one at SPS (the comparison can be made between the slopes quoted in [55] and in the slides [56]).

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[4] Note that the data to theory comparison made in this article should be updated with the newly published PHENIX dAu results from the re-analysis described in [49].

[5] This work is being extended in [50] in order to describe the y-dependence of the peripheral $AuAu$ collisions at RHIC. The first results seem quite promising.

Final-state effects. The so-called "nuclear absorption" has been extensively investigated for the charmonia. It reflects the break-up of correlated $c\bar{c}$ pairs due to inelastic scattering with the remaining nucleons from the incident cold nuclei. As we shall see below, the underlying mechanism is still unclear. Moreover, its physical picture may change with energy, as pointed in [57] and the transition would occur at RHIC energies:

- At low energy, there is a longitudinally-ordered scattering of the heavy-quark pair. It results in an attenuation factor $\exp[-\sigma_{\mathrm{abs}}\rho_0 L(b)]$, where σ_{abs} is the *effective* break-up cross-section, $\rho_0 = 0.17$ nucleon fm^{-3} is the nuclear density and $L(b)$ is the length traversed by the heavy-quark pair in the nuclear matter at a given impact parameter b. The break-up cross-section is not calculable from first-principle QCD[6]. Presently, it is a free parameter in the models, such as in [49] where its value is obtained by fitting the data with a given nuclear shadowing model and an unknown additional absorption. Many considerations are hiding behind the effective value of σ_{abs}. It has been argued [58, 59, 60, 61] that the value of the break-up cross-section should depend both on the collision energy and on the colour state of the created $c\bar{c}$. With increasing collision energy, the pair will hadronise from inside to outside the nucleus. Since a hadronised $c\bar{c}$ is much more robust than the pre-resonance, the effective value of σ_{abs} will decrease with energy. A colour singlet pair has a smaller size and hence a shorter hadronisation time than a colour octet pair, so the corresponding break-up cross-section should be smaller. Moreover, if the direct J/ψ and ψ' are believed to be created perturbatively in the same $c\bar{c}$ octet state, then they should suffer the same amount of nuclear absorption, unless the hadronised states are also broken-up by the scattering off nucleons. A quite rich pA program was developed at SPS, where the CNM effects can be described with the nuclear absorption only: the latest values from the NA50 experiment are [62] $\sigma_{\mathrm{abs}}(J/\psi) = 4.2\pm0.5$ mb and $\sigma_{\mathrm{abs}}(\psi') = 7.7\pm0.9$ mb. However, the quoted value of $\sigma_{\mathrm{abs}}(J/\psi)$ is for the total J/ψ production: it accounts for the absorption of the direct J/ψ as well as of the higher mass $c\bar{c}$ states that would have decayed in J/ψ otherwise. It is also worth remembering that the shadowing effect was "forgotten" when evaluating the quoted values of σ_{abs}. When properly taking into account the anti-shadowing at SPS as in [61], the estimated break-up cross-sections are significantly larger (around 7 mb for the J/ψ and 11 mb for the ψ'). At RHIC, the published values of the effective break-up cross-section in dAu collisions [49] are $\sigma_{\mathrm{abs}}(J/\psi) = 2.8^{+1.7}_{-1.4}(2.2^{+1.6}_{-1.5})$ mb for the two different nPDF/PDF parametrisations used to evaluate the shadowing. However, the shadowing used in [49] is obtained without taking into account the J/ψ's P_T. When doing so, in the $2 \to 2$ process, the resulting shadowing is quite different, leading to a different value of the extracted break-up cross-section [51], which

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[6] It is nevertheless possible to extract its value from photoproduction data $\gamma N \to \psi N$ (see e.g. [47, 48]).

happens to be closer to the published NA50 value.

- At high energy, the above space-time picture of the heavy-quarkonium production in pA should not hold any more. As argued in [57, 63], the heavy state in the projectile will rather undergo a coherent scattering off the target nucleons. The conventional treatment of nuclear absorption is not valid any more and the rigorous method reported in [64] has to be used. As a result, σ_{abs} asymptotically tends to zero at high energies. The required threshold in $\sqrt{s_{NN}}$ for this coherent scattering picture to be relevant is a function of x_+, the longitudinal momentum fraction of the heavy system. The transition happens at RHIC energy for the J/ψ produced at mid rapidity. Consequently, the break-up cross-section is rapidity-dependent at RHIC. In [57, 63], the authors use the method [64] within a Glauber-Gribov description of shadowing to predict the CNM effects on the J/ψ production at various $\sqrt{s_{NN}}$, from 39 GeV to the LHC energies. They report a fair agreement with E866, E772 and PHENIX $p(\text{d})A$ data, both for the rapidity-dependence and the x_F-dependence.

The J/ψ puzzle. As can be seen from the above discussion, disentangling the various CNM effects at work for the J/ψ production in pA is not an easy task. So, in order to set a proper baseline for the QGP search, how can we safely extrapolate the CNM effects from pA to AA ? The current solution adopted by PHENIX [49] is to use the data-driven method inspired by [65] to predict the expected CNM effects in $AuAu$ from the available dAu data. This approach has the advantage of a proper propagation of the experimental errors. The quite annoying drawback is that it is unable to derive any specie- nor energy- dependent extrapolation of the CNM effects.

To improve this situation, we clearly need more and much precise data. At RHIC, the analysis of the latest high statistics dAu run is well under way. At the LHC, a rich pA program will be crucial.

In the meantime, a key test to the models would be to reproduce the observed scaling of the α exponent in $\sigma_{p(\text{d})A} = \sigma_{pp}A^\alpha$, with x_F for the J/ψ production in pA at various $\sqrt{s_{NN}}$. At least three different approaches tried to cope with this observation. A first tentative is done in [59, 60], with a combination of five different types of CNM effects. More recently, with the help of the CGC approach and a simple (single-valued) σ_{abs}, the authors of [46] obtained a result with a reasonable agreement to the observed scaling. In the previous paragraph, we already mentioned the positive result achieved in [57] by the use of a coherent scattering picture of the nuclear absorption and a Gribov-Glauber framework to describe the shadowing.

3.3. *AA* collisions (by Joseph Cugnon)

The interest of heavy-quarkonium production in heavy-ion collisions is twofold. First, these collisions may offer different mechanisms of quarkonium production compared to pp collisions. Second, and more importantly, this production can be used as a sensitive probe to the supposedly formed quark-gluon plasma in the course of these collisions. There is a general consensus that, in the SPS

and RHIC conditions, the quarkonium states (mainly J/ψ) are formed during the first nucleon-nucleon (NN) collisions as in free space and that they are immersed afterwards in the quark-gluon plasma, where they can be dissolved due the screening of the quark-antiquark interaction in the plasma. In these conditions the plasma is rather cold, few charmed quarks are thermally produced and the final J/ψ yield results from the absorption of the early produced charmonium states by the plasma. The situation will be somehow different at the LHC. The temperature of the plasma will be substantially larger, free charmed quarks will be more numerous. Furthermore, charm production will result also from the decay of bottom, which will be produced sizeably at $\sqrt{s_{NN}} = 5.5$ TeV. In addition to the usual formation in first NN collisions, charmonium states will be produced also through the decay of B-mesons and through the fusion of $c\bar{c}$ pairs, either thermally produced directly or through the decays of free b-quarks (the so-called regeneration process). In relation to the use of quarkonia as probes of the plasma, these additional production processes should be clarified both experimentally and theoretically. First the side-feeding in the propagation of excited states in the plasma should be evaluated correctly. It should be reminded that the side-feeding of J/ψ is not yet satisfactorily clarified in the previous experiments [66]. As indicated in Section 2.1, this problem may be circumvented by using the Υ family as probes of the plasma. Nevertheless, the reliable evaluation of the feeding of J/ψ by higher mass resonances in the plasma seems to be a necessary step on the analysis of future experiments. Furthermore, if one is interested in the energy or P_T spectrum of produced quarkonia, the study of the propagation of heavy quarks is highly desired. Progress have been made recently [67], with the use of Fokker-Planck equations (in relation to jet quenching), but the application of this approach is just beginning [68].

The discussion of our present understanding of quarkonium production in terms of known properties of these objects and the supposed properties of the plasma is postponed to Section 6. It probably requires a reliable description of the space-time evolution of the plasma and a good understanding of the interaction between a quarkonium and the surrounding medium. In the past, this problem has been tentatively circumvented by focusing on variables that are hopefully not sensitive to the detail of this evolution. The most popular example is provided by the famous plots of R_{AA} versus L, the estimated average path of the quarkonium inside the plasma and admittedly a very crude variable. This has obvious limitations and does not presently provide a coherent view of the existing experimental data [69]. Therefore, an important effort in order to improve the theoretical description of the evolving plasma is certainly required.

Concerning the coupling of the quarkonia to the plasma, new lattice-QCD developments have taken place recently. There are more and more indications that quarkonia may survive in the plasma up to temperatures of the order of two times the critical temperature T_c [70]. Whether the origin of this property results from unsuspected aspects of the screening properties of the plasma [71] or from other sources is beyond the scope of this overview. As a consequence, the situation at the LHC will be more comfortable than before, since the temperature of the plasma will be higher. In any case, a good theoretical understanding of the coupling is

necessary. It is not granted that this coupling is describable in terms of cross sections for quarkonium-gluon collisions. If it is the case, recent progresses have been made in this field [72], although the variation of the cross section with energy seems to pose problems [66].

Finally, the diagnostic of the plasma will be possible only if the other probes are also well understood: high-P_T photons, dileptons (coming from low mass resonances), etc. The first one is sometimes considered as the ideal probe. However, the present situation is not clear. There are inconsistencies between $AuAu$ and $CuCu$ data [66]. The second one seems to be more distorted than mesonic resonances by medium effects. Further theoretical work is necessary.

4. RECENT THEORETICAL ADVANCES

4.1. QCD corrections (by Jean-Philippe Lansberg)

Recently, substantial progress has been achieved in the computation of higher-order QCD corrections to the hard amplitudes of quarkonium-production processes. The first NLO calculation to date was centered on unpolarised photoproduction of ψ [73] via a colour-singlet (CS) state [74] (that is, LO in v for NRQCD [11]) more than ten years ago now. Later on, NLO corrections were computed for direct $\gamma\gamma$ collisions [75, 76] where it had been shown [77] previously that the CS contribution alone was not able to correctly reproduce the measured rates by DELPHI [78].

At the LHC and the Tevatron, ψ and Υ production proceeds most uniquely via gluon-fusion process. The corresponding cross section at NLO (α_S^4 for hadroproduction processes) are significantly more complicated to compute and became only available one year ago [29, 30]. Those results were recently confirmed in [79, 80]. In the latter papers, the polarisation information was kept and the observable α was also computed. It is important to stress that for ψ and Υ production the CS yields predicted at the NLO accuracy are still clearly below the experimental data. In this respect, the predictions for the polarisation at this order cannot be usefully compared to the data.

Aside from hadroproduction regime, NLO corrections have also recently been computed for two J/ψ-production observables at the B-factories: $J/\psi + c\bar{c}$ [81] and $J/\psi + \eta_c$ [82].

The common feature of these calculations is the significant size of the NLO corrections, in particular for large transverse momenta P_T of the quarkonia when this information is available. In γp an pp collisions, QCD corrections to the CS production open new channels with a different behaviour in P_T which indeed raise substantially the cross section in the large-P_T region. In general, the CS prediction can thus be brought considerably closer to the data, although agreement is only reached at NLO in the photoproduction case [73]. As of today, only the full colour-octet (CO) contributions to direct $\gamma\gamma$ collisions have been evaluated at NLO for $P_T > 0$ [75, 76]. Very recently, CO contributions from S waves ($^1S_0^{[8]}$ and $^3S_1^{[8]}$) have become available [83] for hadroproduction, but their impact on phenomenology has not been fully studied yet. Since NLO corrections do not affect significantly the

P_T dependence, a quick assessment can be obtained via the K factors, the ratios of NLO to LO predictions. The K factors of the cross section at the Tevatron are about 1.2 for the $^1S_0^{[8]}$ state and 1.1 for the $^3S_1^{[8]}$ one (at the LHC, they are both about 0.8). This entails that the value of the CO Long Distance Matrix Elements (LDMEs) fit to the Tevatron data at LO $\langle O\left(^3S_1^{[8]}\right)\rangle \simeq 0.0012$ GeV^3 and $\langle O\left(^1S_0^{[8]}\right)\rangle \simeq 0.0045$ GeV^3 [84] would be at most reduced by 15%. In this respect, the NLO corrections to the octets do not improve the universality of the matrix elements when the idea of the dominance of the CO transitions is confronted to the data on photoproduction from HERA.

In [83], the authors made a fit of the CO LDMEs on prompt data which is not easily comparable to the previous works since it includes feeddown from ψ' and χ_c. It is however worthwhile to note that they had *to abandon* [in the fit] *the experimental data with $P_T < 6$ GeV/c, since it is not possible to obtain a satisfactory P_T distribution in terms of a unique $\langle O_n^H\rangle$ value*. This emphasises the need for more work dedicated to the description of the low-P_T region. Last but not least, the polarisation from CO transitions appears not to be modified at NLO with respect to LO result, thus confirming the flagrant discrepancy between the NRQCD predictions for the polarisation of the J/ψ and the experimental measurements from the CDF collaboration [9].

On the bottomonium side, the situation seems less problematic. We have now at our disposal the CS cross section at NLO including a dominant subset of NNLO corrections at α_S^5 (namely the associated production with 3 light partons) for inclusive Υ hadroproduction [12] at mid and large P_T. The rate obtained by including only the CS channels are in substantial *agreement* with the experimental measurements of the cross section from the Tevatron [13, 14] . Concerning the polarisation, the *direct* yield is predicted to be mostly longitudinal. The experimental data being centered on *prompt* yield [13, 32], we would need first to gain some insights on NLO corrections to P-wave production at $P_T > 0$ to draw further conclusions. Yet, since the yield from P-wave feeddown is likely to give transversely polarised Υ, the trend is more than encouraging.

4.2. Automated generation of quarkonium amplitudes in NRQCD (by Pierre Artoisenet)

The computation of heavy-quarkonium cross section within Non-Relativistic QCD [11] takes advantage of the *small* relative velocity v inside the quarkonium state to factorise in a consistent way perturbative high-energy effects (linked to the heavy-quark-pair production) from non-perturbative low-energy effects (linked to the evolution of the heavy-quark pair into a quarkonium state). This factorisation is performed order by order in α_S (the strong coupling constant) and in v, and is controlled by a factorisation scale Λ. As a result, differential cross sections read

$$d\sigma(\mathcal{Q}) = \sum_n d\hat{\sigma}_\Lambda\left(Q\bar{Q}(n)\right)\langle \mathcal{O}^{\mathcal{Q}}(n)\rangle_\Lambda \tag{2}$$

where n specifies the quantum numbers of the intermediate heavy-quark pair $Q\bar{Q}$. The factors $d\hat{\sigma}_\Lambda\left(Q\bar{Q}(n)\right)$ are called the short-distance coefficients, and can be computed perturbatively in α_S for a given process. The Long-Distance Matrix Elements (LDMEs) $\langle\mathcal{O}^\mathcal{Q}(n)\rangle_\Lambda$ encode the soft evolution of the heavy-quark pair into a quarkonium state. They are universal, i.e., they do not depend on the details of the creation of the heavy-quark pair.

In order to predict the cross section for a given process with a quarkonium in the final state, one has to compute the short distance coefficients at a given accuracy in α_S and in v (which limits the number of transitions n in the sum in Eq. (2)). Even for the tree-level amplitudes, a calculation by hand may be lengthy and in general error-prone, depending on the parton multiplicity in the final state. For the purpose of a fast, easy-to-handle and reliable computation of tree-level quarkonium amplitudes, a new MadGraph-based implementation [85] (MadOnia) has been developed recently. The user may require an S- or a P-wave, colour-singlet (CS) or colour octet (CO) intermediate state, for any process attainable in MadGraph for the open-quark production. The code then generates automatically the related squared amplitude at leading order in v, which can then be interfaced with a phase-space generator to obtain the short-distance cross section. For S-wave state production, the algorithm can also be extended to compute relativistic corrections to the Born-level cross section. For $^3S_1$ states, the decay into leptons can be included, thus giving an easy handle onto polarisation studies. Another capability of the code is the generation of amplitudes involving heavy quarkonium with mixed flavors, such as the B_c.

Several applications of the code have already been reported [12, 30, 33, 85]. One example is the analysis of the associated production of a J/ψ or a Υ plus a heavy-quark pair of the same flavor at the Tevatron. The prediction of differential cross sections as well as polarisation observables, both for CS and CO transitions, is straightforward. One can directly show, for example, that the CS fragmentation approximation, which was used to estimate the $J/\psi + c\bar{c}$ production at the Tevatron, appears to underestimate the yield by a large factor in the region $P_T < 20$ GeV/c.

Beside offering the possibility to check very efficiently the tree-level contribution of a large set of quarkonium production processes, the code is also embedded in a larger project aimed to serve the connection between theory and experiments. At the LHC, J/ψ or Υ hadro-production followed by their leptonic decay will offer a very clean signature to calibrate the detectors as well as to probe new physics effects. Given the large number of such events, one can even hope to reconstruct more exclusive final states, such as $\Upsilon + 2$ b-jets, and hence enlarge the number of measured observables to be compared with theoretical predictions. On the one hand, such measurements rely on theoretical assumptions to establish the criteria for the selection of the signal and to estimate the cut efficiency. On the other hand, theoretical predictions make use of the existing experimental data to quantify non-perturbative low-energy effects, including the values of the LDMEs in the case of quarkonium production.

The flow of information between theory and experiment is made easier by the use of Monte Carlo tools. The new generation of these tools operate in two steps. First they produce parton-level events according to a hard scattering probability

which can be computed perturbatively in α_S. The events are then passed through a code that generates the parton shower and turns the partons into hadrons. Eventually one can use a detector simulator to smear the information according to the resolution of the detector, such that events are as close as possible to real data. For quarkonium production within NRQCD, the relative abundance of parton-level events is controlled by the short distance coefficients appearing in Eq. (2), which can be computed by MadOnia. The algorithm is being currently promoted to an event generator. Spin correlation and colour flow information are kept, such that the unweighted events are ready for parton shower and hadronisation. With such a generator at hand, a large set of studies will become available.

4.3. Other theoretical advances (by Jean-Philippe Lansberg)

On top of the theoretical advances mentioned above, several interesting theoretical results have been obtained in recent years. Let us review some of the most significant ones briefly.

Last year, Collins and Qiu [86] showed that in general the k_T-factorisation theorem does not hold in production of high-transverse-momentum particles in hadron-collision processes, and therefore also for ψ and Υ. This is unfortunate since many studies had been carried out successfully using k_T-factorisation (see references in section 3.3 of [2]), predicting mostly longitudinal yields and smaller CO LDMEs, in better agreement with the idea of LDME universality.

On the side of NRQCD, Nayak, Qiu and Sterman provided an up-to-date proof [87] of NRQCD factorisation holding true at any order in v in the gluon-fragmentation channels. They showed that improved definitions of NRQCD matrix elements were to be used, but that this was not to affect phenomenological studies.

Besides, the c- and b-fragmentation approximation was shown to fail for the P_T ranges accessible in experiments for quarkonium hadroproduction [30]. By studying the entire set of diagrams contributing to ψ and Υ production in association with a heavy-quark pair of the same flavour, it was shown that the full contribution was significantly above (typically of a factor of 3) that obtained in the fragmentation approximation. The latter holds (at 10% accuracy, say) only at very large P_T: $P_T \gtrsim 60$ GeV/c for ψ and $P_T \gtrsim 100$ GeV/c for Υ. Note that the same observation was previously made for the process $\gamma\gamma \to J/\psi c\bar{c}$ [88] and also for the B_c^* hadroproduction, for which it was noticed that the fragmentation approximation was not reliable at the Tevatron [89, 90].

Moreover, still in double-heavy-quark-pair production, the notion of colour-transfer enhancement was introduced by Nayak, Qiu and Sterman [91]. If three out of the four heavy quarks are produced with similar velocities, then there is the possibility that colour exchange within this 3-quark system could turn a CO configurations into CS ones, thus effectively increase the rate of production of CS pairs. They finally discussed the introduction of specific new 3-quark operators of NRQCD necessary to deal with such an issue.

5. PERSPECTIVES FOR SOME (NEW) OBSERVABLES

Standard quarkonium measurements with general purpose detectors at the LHC are generally related to kinematical distributions of the quarkonium decay products, such as differential cross section and polarisation measurements, and focus on decays into muons. Although these provide useful information, it is important to investigate the use of additional observables. In particular, it could be helpful to take into account not only the kinematics of the quarkonium itself, but also that of particles produced in association, or their nature as for instance in the study the production of quarkonia in association with a heavy-quark pair.

5.1. Hadronic activity around the quarkonium
(by A.C. Kraan)

Here, we investigate observables that are sensitive to the hadronic activity directly around the produced quarkonium [92]. This allows to extract information about the radiation emitted off the coloured heavy-quark pair during the production, and thereby about its production mechanism itself. To study the sensitivity of a typical multi-purpose LHC detector, we generated J/ψ and Υ events in PYTHIA 8 [93] in four production toy models: colour-singlet and three colour-octet models with a varying amount of shower evolution of the coloured $Q\bar{Q}$-state.

Because at lower $P_T^{J/\psi}$, shower activity is small in general, differences manifest themselves only at higher values of $P_T^{J/\psi}$, about 20 GeV/c. It must be noted that the energy of the surrounding particles associated with J/ψ-production is small (order GeV), and as such it is not a priori clear whether there is any sensitivity at all over the underlying-event background. Also, a careful understanding of the detector is necessary, so we would not recommend this analysis to be done with early LHC data.

In Fig. 1 (left) we display the transverse momentum density $dP_T/d\Omega_R$ for J/ψ's between 20 and 40 GeV/c after reconstruction, in a cone around the J/ψ of certain size $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, where

$$\frac{dP_T^{around}(R)}{d\Omega_R} = \frac{P_T^{around}(R + dR/2) - P_T^{around}(R - dR/2)}{\pi[(R + dR/2)^2 - (R - dR/2)^2]}. \tag{3}$$

Here $P_T^{around}(R)$ is the sum of the transverse momentum of all charged particles (with $P_T > 0.9$ GeV/c) inside the cone of size R. In Fig. 1 (right) we display this variable for prompt $\Upsilon(1S)$-events. For Υ-events the activity is lower than that for J/ψ-events because the $b\bar{b}$ is heavier than the $c\bar{c}$ state, and thus has a smaller shower evolution.

For prompt J/ψ's, the main background comes from non-prompt J/ψ production. Whether one can subtract the background component from data in order to obtain the hadronic activity related to prompt production remains to be seen. For Υ's, the situation is easier: the background can be studied accurately by studying the events in the side-bands.
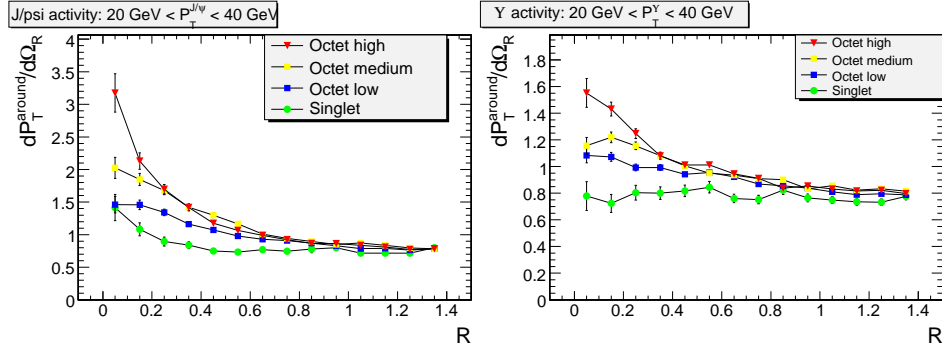
FIGURE 1. Variable $dP_T^{around}(R)/d\Omega_R$ at reconstruction level for J/ψ (left) and $\Upsilon(1S)$ (right) events.

5.2. Associated production channels (by Jean-Philippe Lansberg)

Another very valuable observable, likely to test the many production models available [1, 2], is the study of associated production channels, first in pp collisions, then in pA and AA. By associated production channels, we refer to $\psi + c\bar{c}$ and $\Upsilon + b\bar{b}$.

A first motivation for such studies is simple: similar studies carried at B-factories showed an amazingly large fraction of J/ψ production in association with another $c\bar{c}$ pair. Indeed, Belle collaboration first found [94] $\frac{\sigma(e^+e^- \to J/\psi + c\bar{c})}{\sigma(e^+e^- \to J/\psi + X)}$ to be $0.59^{-0.13}_{+0.15} \pm 0.12$. Thereafter, the analysis was improved and they obtained [95]

$$\frac{\sigma(e^+e^- \to J/\psi + c\bar{c})}{\sigma(e^+e^- \to J/\psi + X)} = 0.82 \pm 0.15 \pm 0.14, \tag{4}$$
$$> 0.48 \text{ at } 95\% \text{ CL}.$$

Whether or not such a high fraction holds for hadroproduction as well, is a question which remains unanswered. Analyses at the Tevatron (CDF and $D\emptyset$) and at RHIC (PHENIX and STAR) are already possible. As computed in [30] for the RUN2 at the Tevatron at $\sqrt{s} = 1.96$ TeV, the integrated cross-section are significant (see Fig. 2 for the J/ψ):

$$\sigma(J/\psi + c\bar{c}) \times \mathcal{B}(\ell^+\ell^-) \simeq 1 \text{ nb}$$
$$\sigma(\Upsilon + b\bar{b}) \times \mathcal{B}(\ell^+\ell^-) \simeq 1 \text{ pb} \tag{5}$$

Without taking into account any modifications of the CO LDMEs induced by the QCD corrections mentioned in Section 4.1, the integrated cross sections were found in [33] to be dominated by the CS part, similarly to the differential cross section in P_T up to at least 5 GeV/c for ψ and 10 GeV/c for Υ. In other words, such observables can be thought of as a test of the CS contribution, for the first time since the idea that CO transitions would be the dominant mechanism responsible
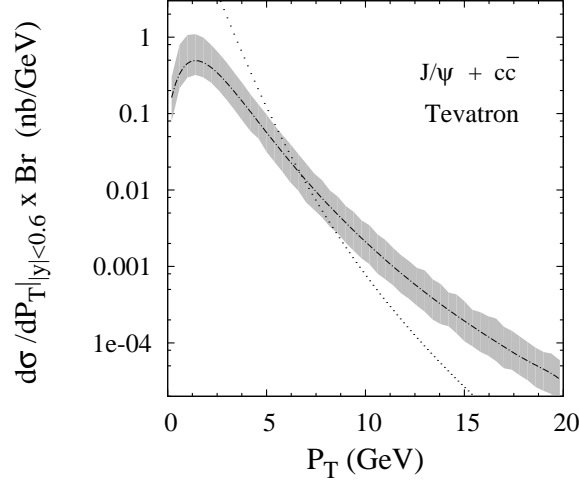
FIGURE 2. Differential cross section for $pp \to J/\psi + c\bar{c}$ as function of the J/ψ transverse momentum P_T at the Tevatron ($\sqrt{s} = 1.96$ TeV).

for quarkonium production at high transverse momentum. If the effect of CO transitions is confirmed to be negigible for the Υ, the Υ produced in association with a $b\bar{b}$ pair are predicted to be strictly unpolarised, for any P_T (see Fig. 3).
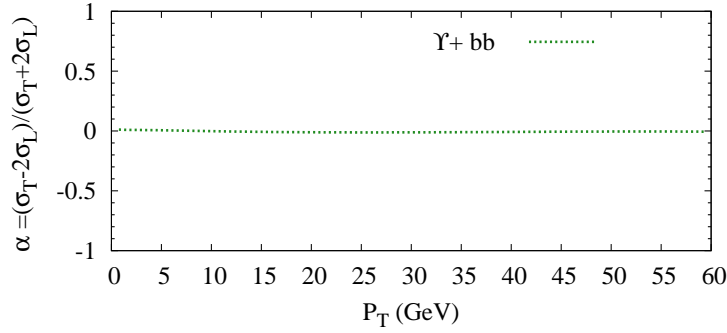

FIGURE 3. Polarisation of an Υ produced in association with a $b\bar{b}$ pair at the Tevatron for $\sqrt{s} = 1.96$ TeV for $|y| \le 0.6$.

Beside the property of discriminating between the CO and the CS transitions, the yield of ψ in association with $c\bar{c}$ should be a priori less sensitive to the χ_c feeddown and B feeddown (and Υ with $b\bar{b}$ insensitive to the χ_b feeddown). Indeed, being suppressed by the relative velocity, the P-wave yield is expected to be smaller than the CS S-waves[7]. Note that the situation is completely at variance with the

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[7] To be complete, let us mention the possibility to produce $\chi_c + c\bar{c}$ via the process $gg \to gg$ for which the two final-state gluons split into a $c\bar{c}$ pair, one of them habronising into a χ_c via the CO mechanism. This contribution is certainly suppressed up to $P_T \simeq 20$ GeV. For larger P_T, a

inclusive case for which it is nearly always easier to produce a P-wave than a ψ since this requires one less gluon attached to the heavy-quark loop. Concerning the ψ feeddown from B, the same is expected to occur: there are only prices to pay to produce a ψ via a B with a $c\bar{c}$ (heavier quark mass and then decay into a ψ) while no gain in the P_T dependence since both $B(\to \psi X) + c\bar{c}$ and $\psi + c\bar{c}$ cross sections scale like P_T^{-4}.

Let us also mention that associated production has also been studied in direct $\gamma\gamma$ collisions in Ultra-peripheral collision (UPC) [96]. At least for direct $\gamma\gamma$ collisions, associated production is the dominant contribution to the inclusive rate for $P_T \geq$ 2 GeV/c.

To conclude, let us mention that studies can be carried on by detecting either the "near" or "away" heavy-quark with respect to the quarkonia. There are of course different way to detect the D, B, or a b-jet, ranging from the use of a displaced vertex to the detection of their decay in e or μ. This has to be considered by also taking into account the different backgrounds. In any case, we hope that such measurements would provide with clear information on the mechanism at work in quarkonium production.

5.3. Exclusive quarkonium photoproduction in proton and nucleus colliders (by David d'Enterria)

A significant fraction of proton-proton and ion-ion collisions at collider energies involve "ultraperipheral" electromagnetic interactions characterised (in the Weizsäcker-William equivalent-photon-approximation [97]) by the exchange of a quasi-real photon. Exclusive quarkonium photoproduction at proton or nucleus colliders – i.e. processes of the type $\gamma h \to V h$ where $V = J/\psi, \Upsilon$ and the hadron h (which can be a proton or a nucleus A) remains intact – has been measured at RHIC [98] and the Tevatron [99] and will be measured at the LHC in both pp [100] and pPb and $PbPb$ [101] collisions. Exclusive $Q\bar{Q}$ photoproduction offers an attractive opportunity to constrain the low-x gluon density at moderate virtualities, since in such processes the gluon couples *directly* to the c or b quarks (see Fig. 4) and the cross section is proportional to the gluon density *squared* (see [102] and refs. therein). The mass of the $Q\bar{Q}$ vector meson introduces a relatively large scale, amenable to a perturbative QCD (pQCD) treatment. In the case of nuclei, the information provided by such processes is especially important since the gluon density is very poorly known at low-x and there are not many experimental handles to measure it in a "clean" environment [103].

The CDF collaboration has recently reported preliminary measurements of exclusive J/ψ, ψ' and Υ photoproduction in the dimuon decay channel in p-$\bar{\text{p}}$

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dedicated calculation is needed. However, this mechansim would be very easily disentangled from the CS contributions since both c quarks are necessarily emitted back to back to the χ_c and thus to the J/ψ.
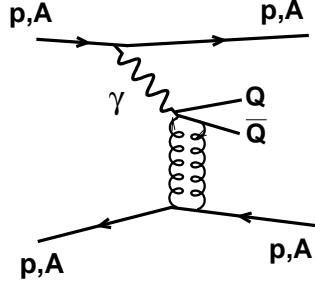
FIGURE 4. Schematic diagram for exclusive diffractive quarkonium photoproduction in γA, γp collisions collisions.

collisions at 1.96 TeV [99]. The $c\bar{c}$ states can be very well observed above a small dimuon continuum from $\gamma\gamma$ interactions (Fig. 5, left). The data is compared to photon-pomeron predictions as implemented in the STARLIGHT Monte Carlo [104] in order to try to pinpoint a possible excess which could be indicative of photon-odderon J/ψ production. At higher masses the $\Upsilon(1S)$ and $\Upsilon(2S)$ are also clearly visible. Similar simulation studies in pp collisions at the LHC have been carried out by ALICE [105] and CMS [100].

In Ultra-Peripheral Collisions (UPCs) of heavy-ions the maximum photon energies attainable are $\omega_{max} \approx 3$ GeV (100 GeV) at RHIC (LHC). Correspondingly, the maximum photon-nucleus c.m. energies are of the order $W_{\gamma A}^{max} \approx 35$ GeV (1 TeV) at RHIC (LHC). Thus, in $\gamma A \to J/\psi\,(\Upsilon)\,A^{(*)}$ processes, the gluon distribution can be probed at values as low as $x = M_V^2/W_{\gamma A}^2 \approx 10^{-2}(10^{-4})$. At low-$x$, gluon saturation effects are expected to reveal themselves through strong suppression of hard-exclusive diffraction relative to leading-twist shadowing [106]. While this suppression may be beyond the kinematics achievable for J/ψ photoproduction in UPCs at RHIC, $x \approx 0.01$ and $Q_{\text{eff}}^2 \approx M_V^2/4 \approx 3$ GeV^2, it could be important in UPCs at the LHC [101].

The PHENIX experiment has measured J/ψ photoproduction at mid-rapidity in Au-Au UPCs at $\sqrt{s_{NN}} = 200$ GeV in the dielectron channel [98]. Within the (still large) experimental errors, the preliminary J/ψ cross-section of $d\sigma/dy|_{|y|<0.5} = 48 \pm 14(\text{stat}) \pm 16(\text{syst})$ μb is consistent with various theoretical predictions [104, 107, 108, 109] (Fig. 5, right). The band covered by the FGS predictions includes the J/ψ cross sections with and without gluon shadowing [107]. Unfortunately, the current statistical uncertainties preclude yet any detailed conclusion regarding the nuclear gluon distribution.

At the LHC energies, the cross section for $\Upsilon(1S)$ photoproduction in UPC *PbPb* at $\sqrt{s_{NN}} = 5.5$ TeV is of the order of 150 μb [104, 110]. Inclusion of leading-twist shadowing effects in the nuclear PDFs reduces the yield by up to a factor of two, $\sigma_\Upsilon = 78$ μb [110]. Even larger reductions are expected in calculations including gluon-saturation (Colour Glass Condensate) effects [111]. Full simulation studies of input distributions generated with the STARLIGHT MC [104] have shown
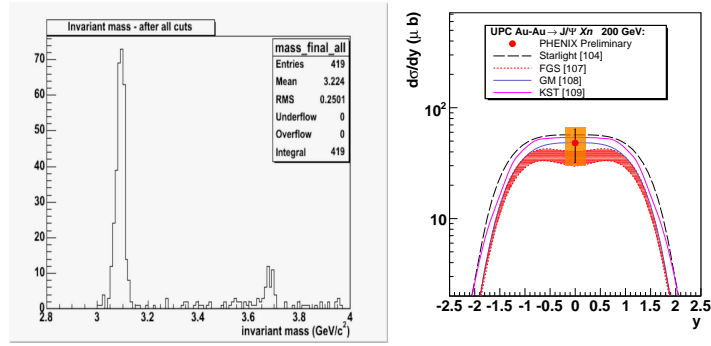
FIGURE 5. Left: Invariant mass distribution of $\mu^+\mu^-$ pairs measured in exclusive p$\bar{\text{p}}$ collisions by CDF at 1.96 TeV [99]. Right: Preliminary cross-section of coherent J/ψ production at $y = 0$ in UPC Au-Au at $\sqrt{s_{NN}} = 200$ GeV [98] compared to various theoretical calculations [104, 107, 108, 109].

that ALICE [105] and CMS [22] can measure well $J/\psi \to e^+e^-$, $\mu^+\mu^-$ and $\Upsilon \to e^+e^-$, $\mu^+\mu^-$ respectively (in different pseudorapidity ranges) in UPCs tagged with neutrons detected in the ZDCs.

5.4. Bottomonium dissociation at the LHC (by David Blaschke)

A lot of progresses have been made in the experimental and theoretical investigations of charmonium production in heavy-ion collisions, see [112] for a recent review. Although CERN-SPS data from the NA50 and NA60 collaborations have provided a clear evidence for an anomalous J/ψ suppression pattern, an unambiguous theoretical approach to the phenomenon is still lacking. As elements for such an approach are being assembled, it becomes clear that theoretical models have to be supplemented by measurements of nonperturbative phenomena such as to provide baselines for new physics, i.e. for the studies of heavy quarkonia in hot dense matter as produced in high-energy AA collisions.

While the situation with charmonium production becomes more and more complex and puzzling when comparing SPS and RHIC experiments due to intricate intertwining of nonperturbative initial-state, formation-stage and final-state effects (see Section 3.2), the bottomonium spectroscopy accessible in the upcoming LHC experiments may offer a much cleaner probe of the physics of dense matter. This is due to the following specificities of the heavier $b\bar{b}$ system relative to the $c\bar{c}$ system: (i) absence of down-feeding from a heavier quarkonium system, (ii) negligible regeneration of bottom quarks from the thermal medium, (iii) dominance of Coulombic part of the $b\bar{b}$ interaction and partonic medium, so that plasma screening and thermal dissociation effects shall be under better control, (iv) both low-lying states, $\Upsilon(1S)$ and $\Upsilon'(2S)$ are bound states in the temperature range $T = 1 \ldots 2\, T_c$, and are thus well-separated from the hadronisation stage.

Here we would like to review some first baseline estimates of bottomonium spectroscopy for the discussion of upcoming experiments at the LHC and their

impact on the discussion of quark-gluon plasma (QGP) properties. Due to the above characteristics, bottomonium production at the LHC will allow to test the kinetic approach to heavy-quarkonium dissociation by thermal activation in a quark plasma. In this approach the survival probability is given by

$$
\begin{aligned}
S_\Psi &= S_{\mathrm{HG}} \, S_{\mathrm{QGP}} \, S_{\mathrm{nuc}} \\
&\simeq \exp\left(-\int_{T_c}^{T_{fo}} \Gamma_{\mathrm{HG}}(T)\frac{dT}{\dot{T}}\right) \, \exp\left(-\int_{T_c}^{T_0} \Gamma_{\mathrm{QGP}}(T)\frac{dT}{\dot{T}}\right) \, \exp\left(-n_N \sigma_{\mathrm{abs}} L\right). (6)
\end{aligned}
$$

where the quarkonium dissociation rate (inverse lifetime) in a QGP is determined by the thermally averaged breakup cross sections by (massless) quark and gluon impact

$$
\Gamma_{\mathrm{QGP}}(T) = \frac{1}{\tau_{\mathrm{QGP}}(T)} = \sum_{i=q,g} \frac{1}{2\pi^2} \int_0^\infty \omega^2 d\omega \, \sigma_{(Q\bar{Q})i}(\omega) v_{\mathrm{rel}} n_i(\omega) . \tag{7}
$$

The dominant medium effect on the dissociation rate is given by the temperature dependence of the binding energy, i.e. the energy necessary to excite the quarkonium state to the continuum threshold where it can perform rearrangement reactions to open flavor states without energy cost. These inputs are provided from solutions of the heavy-quarkonium Schrödinger equation with a temperature-dependent heavy-quark potential, see Figs. 6 and 7. While the binding energies for J/ψ and Υ' drop to zero for temperatures just above T_c, the Υ is a bound state up to at least 2.2 T_c. The absolute value of the binding energy is below the thermal energy of the impacting partons $\sim T$ and therefore the Υ production shall be dominated by thermal dissociation processes.
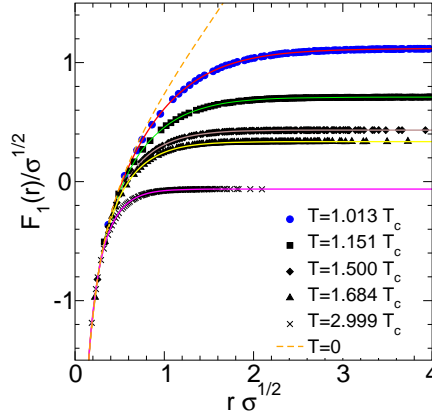

FIGURE 6.   The colour singlet $Q\bar{Q}$ free energy $F(r,T)$ vs. r at different T [113, 114].

For the importance of the in-medium modification of the threshold, we want to refer to processes with quark impact, described by the Bethe-Born model (BBM) or the string-flip model (SFM), see [116] and references therein, results are shown in Fig. 8, left panel. Corresponding results for gluon-induced processes have recently
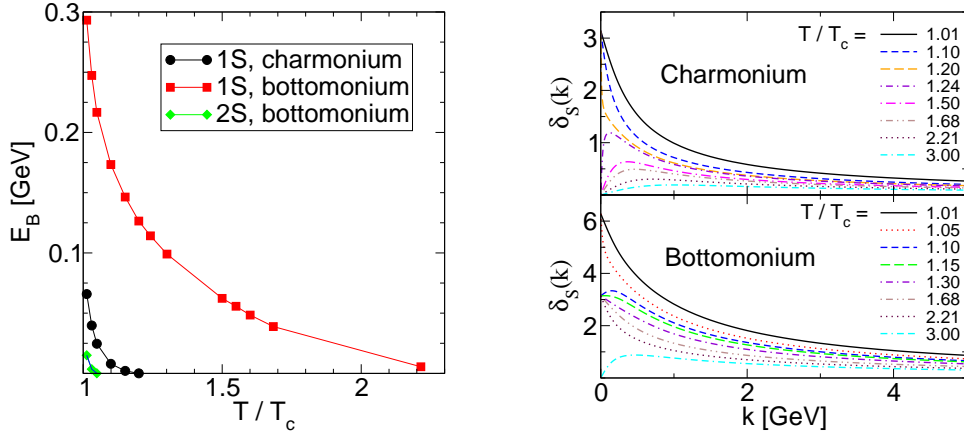
FIGURE 7. Solutions of the Schrödinger equation for heavy quarkonia with the screened potential identified with the singlet free energies of the left panel: binding energies (left) and scattering phase shifts (right), from [115].
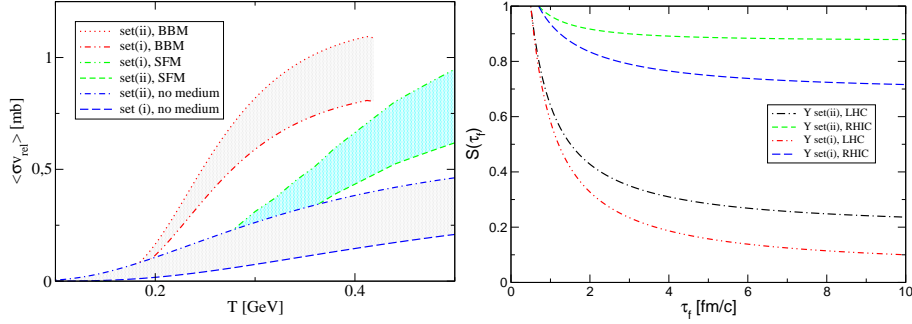

FIGURE 8. Left panel: thermally averaged cross section for Υ dissociation by quark impact as a function of the temperature: BBM and SFM approach give a similar cross section enhancement due to the lowering of the breakup threshold, from Ref. [116]. Right panel: Survival probability for Υ in a longitudinally expanding gluon plasma as a function of the plasma lifetime, from Ref. [4].

been discussed in [117]. The right panel of Fig. 8 gives a rough estimate at which level Υ suppression by thermal dissociation in a QGP is to be expected. A more detailed discussion of bottomonium dissociation at RHIC and the LHC can be found in [118].

Summarizing, we want to emphasise the role of precise bottomonium spectroscopy in AA collisions at the LHC for the diagnostics of QGP properties, such as temperature and lifetime. A key role for the extraction of these properties do play microscopic theories for dissociation reactions of the states of the $b\bar{b}$ spectrum with their kinematic dependences.

6. BRIDGING THE GAP BETWEEN pp AND AA
(by Joseph Cugnon)

This section is devoted to a few remarks on the actual understanding of quarkonium production in heavy-ion collisions in terms of the present knowledge of the properties of quarkonium production in free space, of the properties of the quarkonium and on the heavy-ion collision dynamics.

Of course, this survey starts with the status of the theoretical description of the quarkonium production in NN collisions. The traditional idea of a gluon fusion followed by the colour-octet mechanism seems to fail to reproduce the CDF data. However, this idea within a colour-singlet picture has been reconciled recently with the data for J/ψ at low P_T [28] . In a simple language, the interaction between the c and $\bar{c}$ quarks has been added.

As said in Section 3.3, the conventional belief is that, in heavy-ion collisions, quarkonium states are produced in the first NN collisions, similarly as in free space. This is however probably not true. At high energy, the incoming heavy-ions should be regarded as fluxes of partons. The latter may not be involved only in the first collisions. The fluxes at the moment of interaction may be altered. These "initial state effects" on the parton distributions have been invoked to describe the y and P_T J/ψ distribution in heavy-ion collisions. It seems that these distributions can be described by advocating either the $c\bar{c}$ interaction or the broadening of the k_T distribution of the initial gluons [69].

Let us now examine the status of the so-called J/ψ suppression. The original idea by Matsui and Satz [6] is that the screening of the colour forces inside a plasma leads to the eventual dissociation of quarkonium states. Expecting such a plasma in heavy-ion collisions at sufficiently large energy, it was predicted that the J/ψ yield should be reduced. Since the original yield is not known, the idea is to look at the relative yield as a function of the path length in the plasma (in the famous R_{AA} versus L plot). And indeed, such a suppression was observed in the NA38 experiment soon after. In the meantime, Hüfner and collaborators showed that such a suppression is obtained in a simple multiple NN collision picture, provided an inelastic J/ψ-nucleon inelastic cross section of a few mb is used [119]. This result shed some trouble for a while, but nobody believes in this scenario any more. Evidences for J/ψ suppression has been accumulated, even if they are not always consistent. This is not considered as a proof of the existence of the plasma, for several reasons. First, the energy spectra of the produced particles do not show temperatures above T_c (see the interesting discussion of H. Satz in these proceedings [120]). The alternative probes of the plasma do not give clear-cut answers. Furthermore, the J/ψ suppression can be accounted for thanks to several alternative scenarios (comovers, meson gas or fluid).

Interesting developments have taken place in the recent years. There is more and more evidence that quarkonia survive in the plasma up to temperatures of the order of $2T_c$ [70], indicating that the transition would not be a pure second order phase transition but rather of the Kosterlitz-Thouless type [71]. Therefore, the coupling of a quarkonium state and the plasma has to be re-examined. The J/ψ-gluon inelastic cross section has been re-evaluated recently to take into account this partial

screening [72, 121]. Furthermore, the higher-mass resonances are not automatically dissolved. They should increase the J/ψ yield. Therefore it has been suggested that the observed J/ψ suppression is largely coming from the disappearance of these resonances (the so-called "direct" suppression). The evidence of that is controversial and there is little hope that experiments at the LHC will clarify the issue (see Section 4.3).

In the recent years, attention has been put on open c and open b production through charmed and bottomed mesons and/or jets driven by c or b quarks. In particular, the P_T-dependence indicates a strong suppression, contrasting with the small suppression of quarkonium (even no suppression at large P_T; incidentally, the interest in the P_T-dependence of J/ψ suppression has been so luckily revived, this variable being less ambiguous than the L variable or equivalent). This has raised a strong interest in the energy loss of a heavy quark in the plasma. According to some authors [69, 122, 123], the radiative energy loss in colour fields may lead to an upper bound of the final parton energy, expressed as

$$E_{bound} = \frac{2\pi}{\sqrt{\lambda}} \frac{m^4}{F^2} \frac{1}{L} \qquad (8)$$

where m is the mass of the quark, L is the path length and F is the colour force. This results from the so-called AdS/CFT correspondence and crucially depends upon the fact that the specific energy loss is proportional to the square of the energy in such an approach. From reasonable estimates, the previous equation leads to

$$E_{bound}(\text{GeV}) \leq \frac{\xi}{L(\text{fm})} \qquad (9)$$

where ξ=1 for c and 14 for b quarks. If this is true, heavy-quark production will be limited to surface emission only. In addition, recent measurements indicate that c and b quarks participate to the flow, which even complicates the picture of the propagation inside the plasma. Definitely, this issue warrants further investigation.

In conclusion, if there has been undeniable theoretical progress on various aspects of the production of quarkonium in the recent years, one has to admit that our understanding is still far from complete.

7. CONCLUSION

On the verge of the start-up of the LHC, an overview of the current knowledge of heavy-quarkonium production reveals a situation that is somehow still not satisfactory. In proton-proton collisions, the interest of this process stems from the simple observation that the rather large scale introduced by the heavy-quark mass allows a separation between perturbative and non-perturbative physics, opening up the way to a first principle description. However, given the present data, the effectiveness of such an approach is yet to be confirmed.

Concerning nucleus-nucleus collisions, the status of J/ψ suppression as an indicator of the formation of the quark-gluon plasma (QGP) is also becoming more

shaky. There has been a great effort to use proton-nucleus collisions to evaluate the so-called Cold Nuclear Matter (CNM) effects on the J/ψ suppression in the recent years.

Yet the situation appeared more complicated than expected concerning the nuclear parton distribution functions (nPDFs) at low x and their dynamical evolution. Although novel experimental observables, like e.g. quarkonium photoproduction in ultra-peripheral nucleus-nucleus collisions, provide a new handle to shed light on these issues. The influence of the QGP on the suppression is not really transparent: the understanding of the screening of colour charges above the critical temperature, of the coupling of the heavy quarkonium to the plasma and of its time evolution seems to be less solid than a few years ago.

On the other hand, several aspects are promising, most of them being related to the advent of the LHC beams. As for heavy-quarkonium production in proton-proton collisions, the possibility of bottomonium production, of measurements of polarisation and associated production of J/ψ and of Υ with a heavy-quark pair will severely constrain the current theoretical models. As for proton-nucleus collisions the analysis of the dAu data at RHIC and the set-up of an elaborated pA program are certainly of importance and promising of future programs.

Finally, for nucleus-nucleus collisions, the LHC will offer new possibilities: higher temperatures of the plasma and production of Υ states, which are expected to clarify the analysis. Theoretical advances concerning the interaction of the heavy quarkonia with the hot plasma, the slowing down of heavy quarks and the space-time evolution of the plasma are expected. Those advances are anyhow necessary.

ACKNOWLEDGMENTS

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